Higgs results from ATLAS

Xin Chen

Tsinghua University

On behalf of the ATLAS Collaboration

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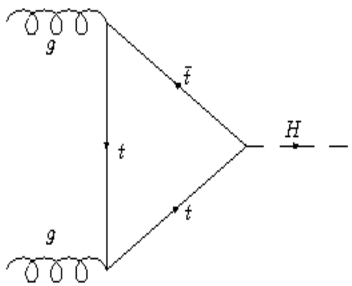
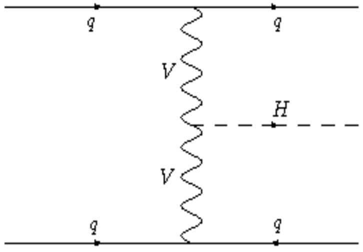
Higgs search channels

Higgs production channels at LHC:



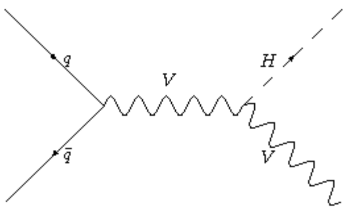
(1)

Gluon-gluon fusion



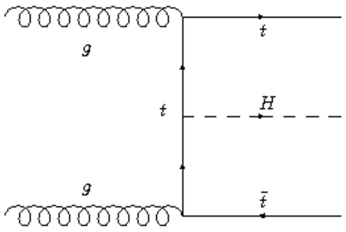
(2)

Vector-boson fusion



(3)

VH Associated

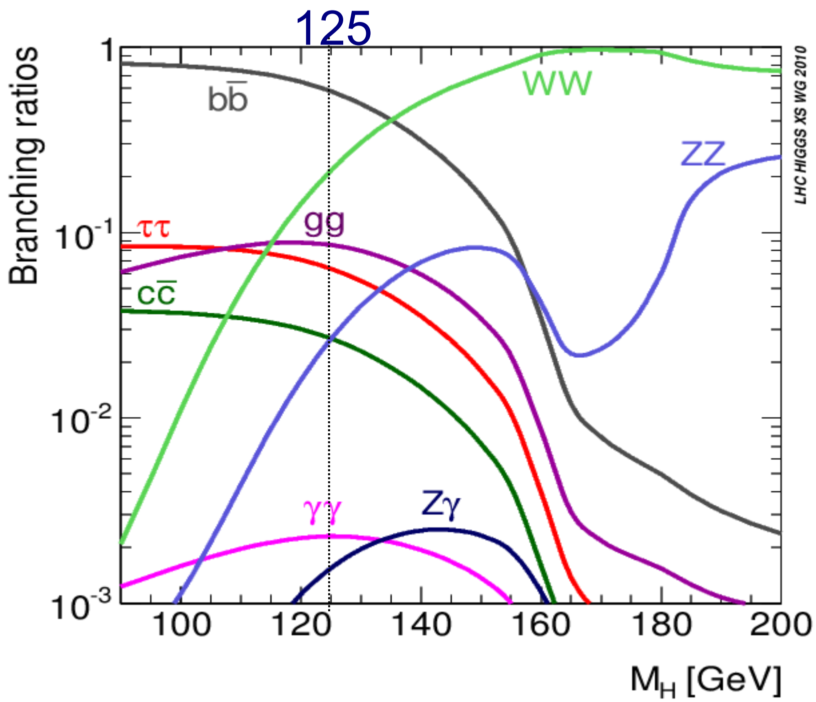


(4)

ttH

Branching ratios for a Higgs mass of 125 GeV:

channel	BR
bbar	57.7%
WW	21.5%
ττ	6.3%
ZZ	2.6%
γγ	0.23%



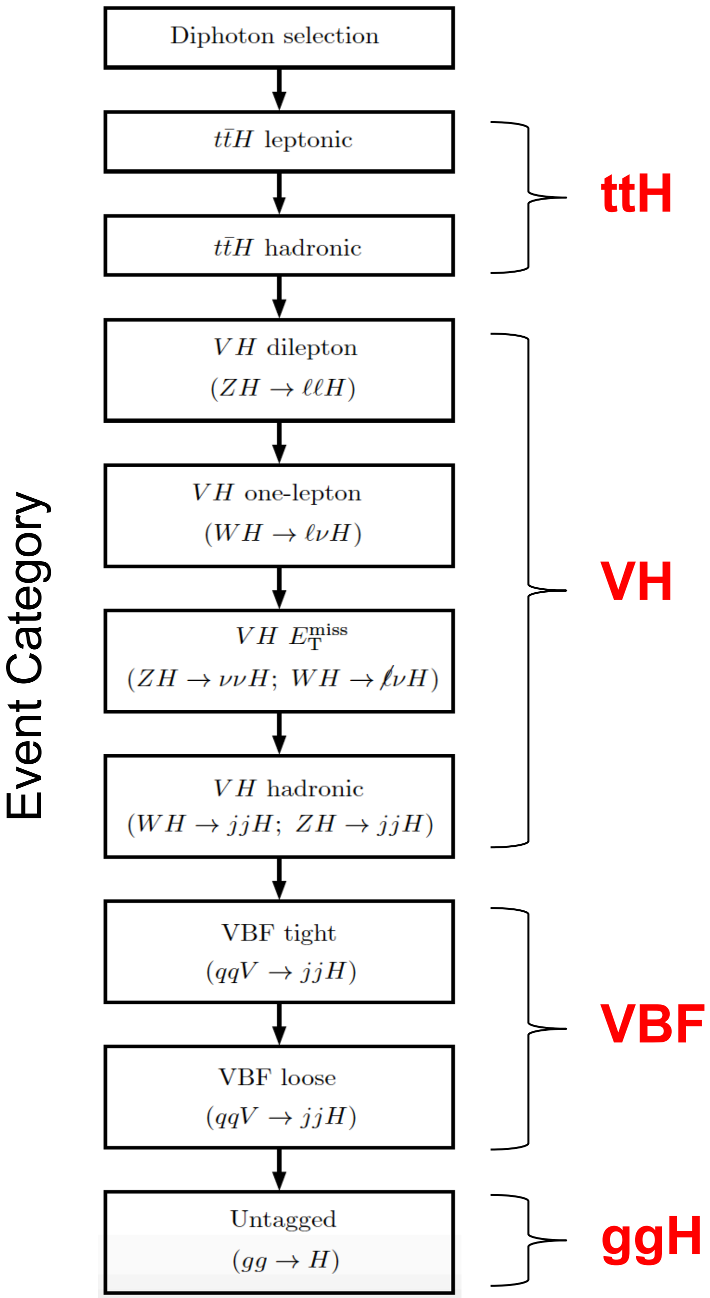
Theoretical limits:

NNLO/NNLL QCD + NLO EWK calculations of Higgs ggF (VBF) production cross sections with ~8% (0.6%) scale and ~7% (1.7%) PDF+α_s uncertainties

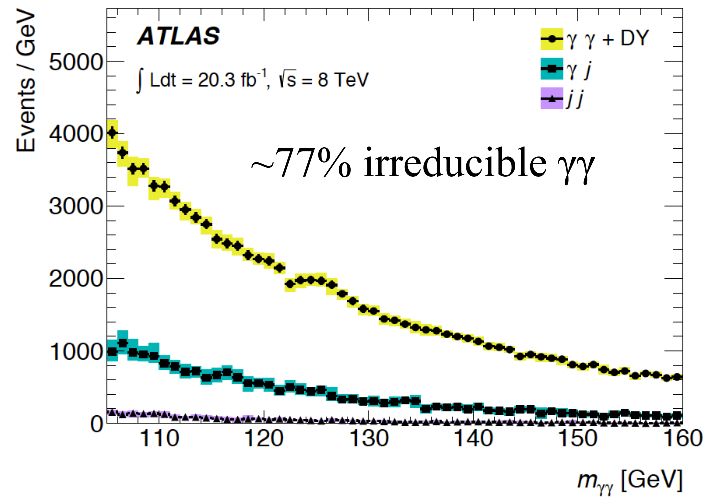
Branching ratios with typically ~5% error

[Phys. Rev. D 90 (2014) 112015]

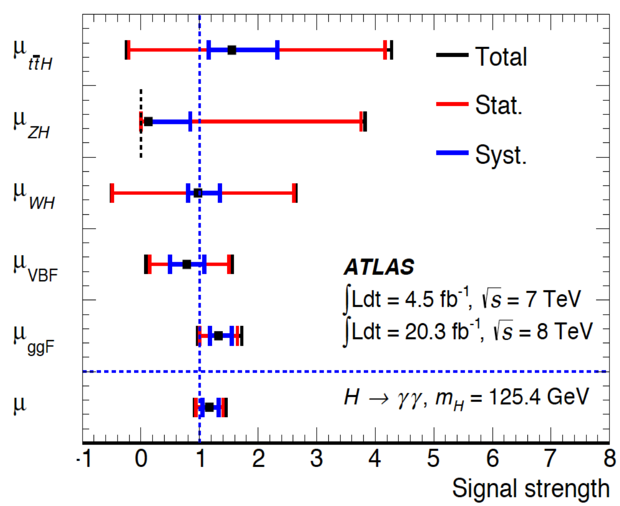
H→γγ updated

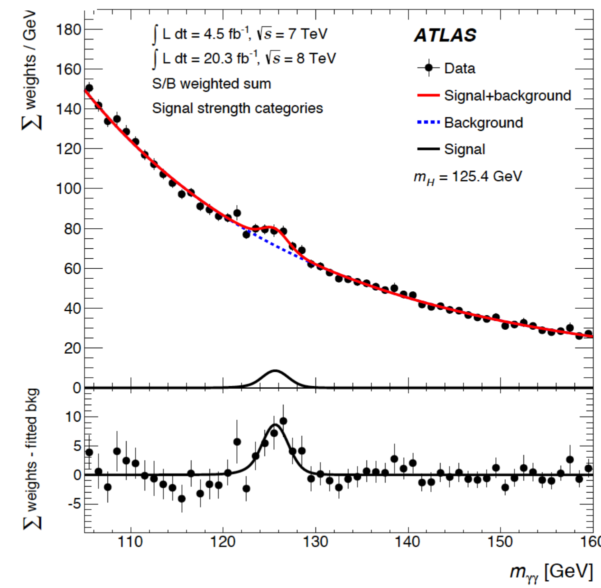


Background composition



- Irreducible γγ background (σ≈40 pb, theo. error ~20%)
- Reducible background: γ+jet (σ≈μb), and jet+jet (σ≈mb): mainly π^0 faking photon – hard to model with simulation, have to rely on data



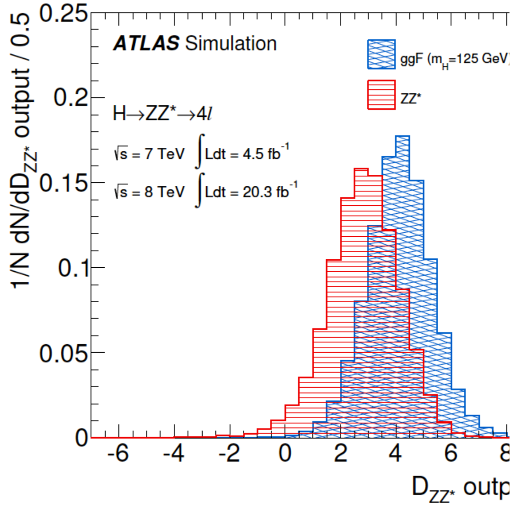


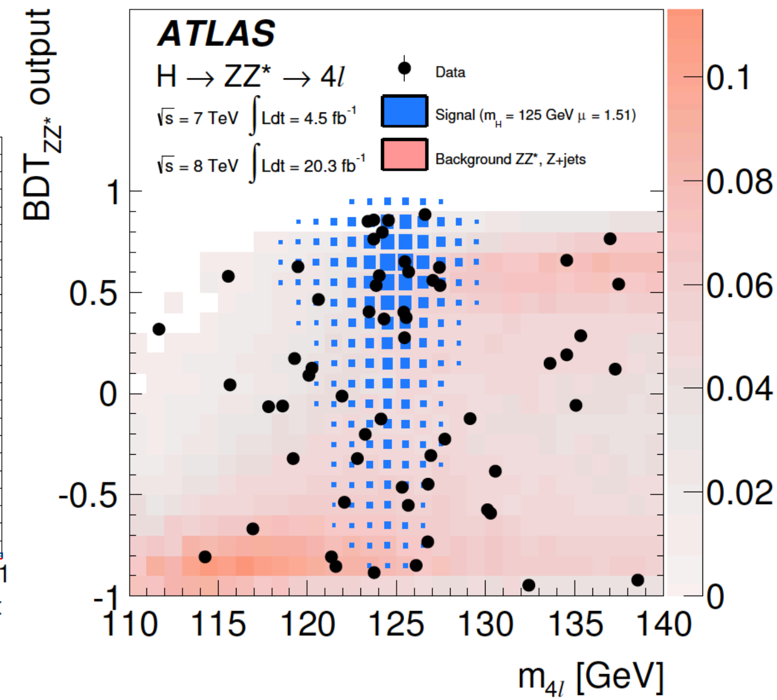
Signal strength: $\mu = 1.17 \pm 0.27$

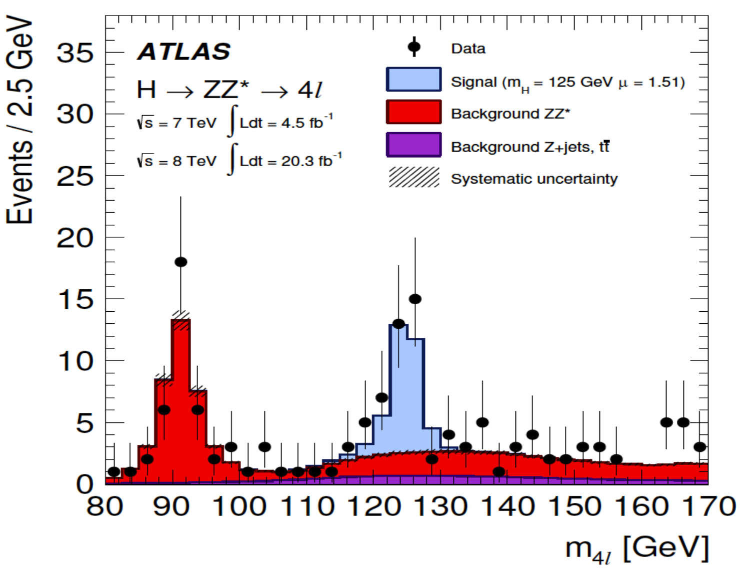
[Phys. Rev. D 91 (2015) 012006]

H→ZZ→4l updated

Very rich final state phase space – exploit Matrix Element discriminant and Boosted Decision Trees (BDT) methods:







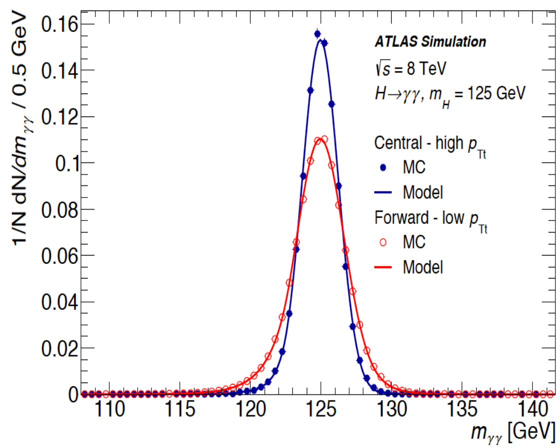
Small rate: BR(ZZ→4l)~0.45%, σxBR(H→ZZ→4l)~2.6 fb
Lepton p_T>20/15/10/6-7 GeV, 50<m_{12}<106 GeV, 12-50<m_{34} <115 GeV
Devided into VBF, VH and ggH enriched region
Main background is ZZ* and Zbb – invert isolation or d0 to estimate Zbb

Signal strength: $\mu \times B / B_{SM} = 1.44^{+0.34}_{-0.31}(\text{stat})^{+0.21}_{-0.11}(\text{sys})$

Higgs Mass measurement

categories	width	s/b (%)
Inclusive	1.67	3.39
Unconv. central low p_{Tt}	1.35	6.66
Unconv. central high p_{Tt}	1.21	24.6
Unconv. rest low p_{Tt}	1.53	3.30
Unconv. rest high p_{Tt}	1.36	9.95
Unconv. transition	1.86	2.57
Conv. central low p_{Tt}	1.52	5.69
Conv. central high p_{Tt}	1.35	19.4
Conv. rest low p_{Tt}	1.88	2.52
Conv. rest high p_{Tt}	1.64	7.44
Conv. transition	2.41	1.92

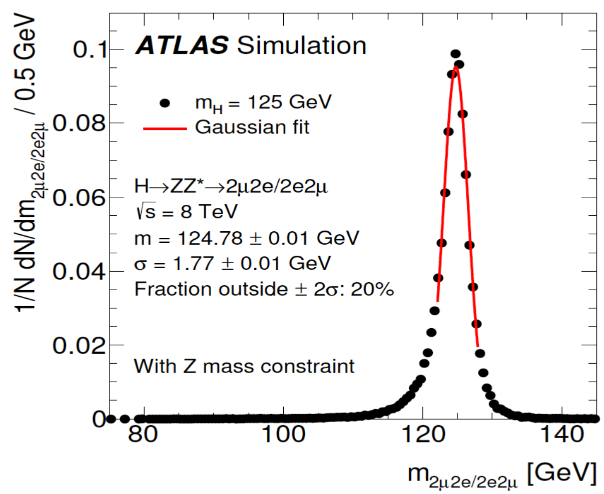
Classify events for best mass resolution



H→γγ : $125.98 \pm 0.42\,(\mathrm{stat}) \pm 0.28\,(\mathrm{syst})$

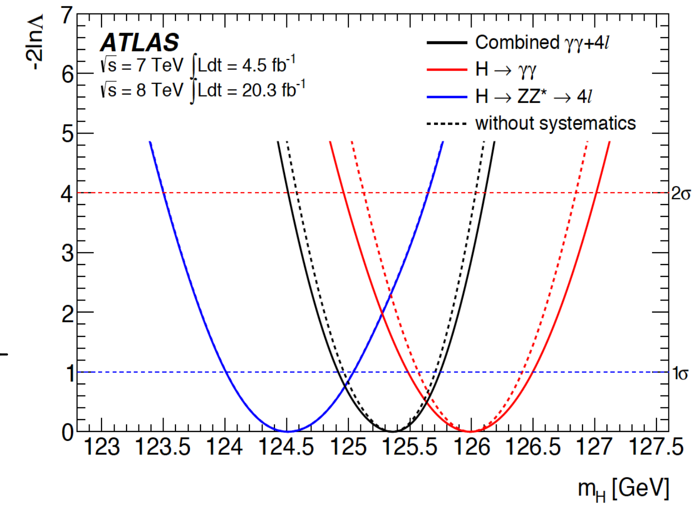
Similar to coupling measurement, fit 2-dim PDF of mass to the BDT output

Z mass constraint improves Higgs mass resolution by ~15%



H→4l : $124.51 \pm 0.52\,(\mathrm{stat}) \pm 0.06\,(\mathrm{syst})$

[Phys. Rev. D 90 (2014) 052004]



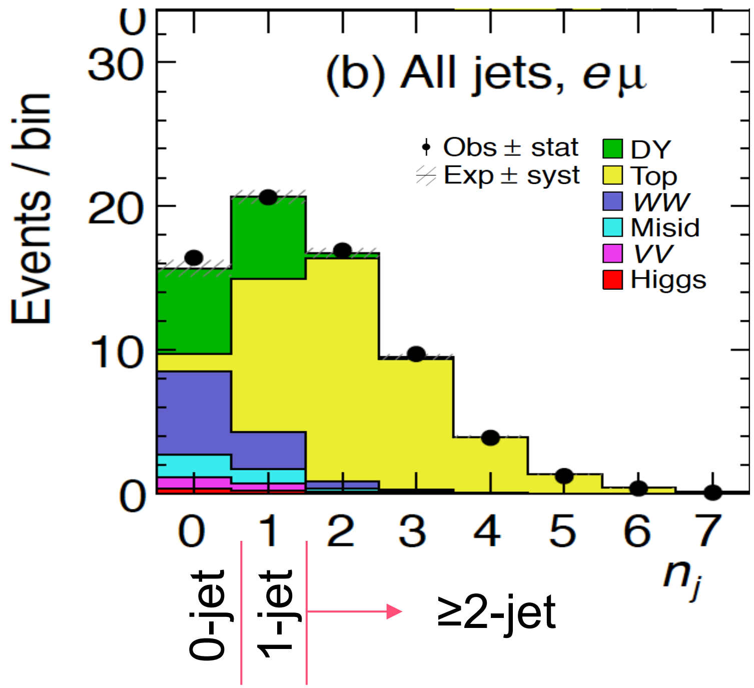
Combined mass measurement:

$125.36 \pm 0.37\,(\mathrm{stat}) \pm 0.18\,(\mathrm{syst})$

The compatibility of the two measurements are at 2σ level (4.8%)

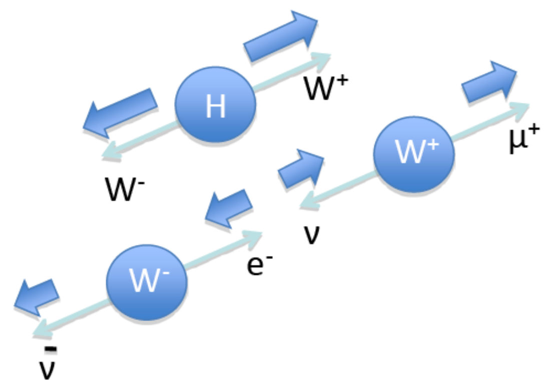
H→WW→2l2ν

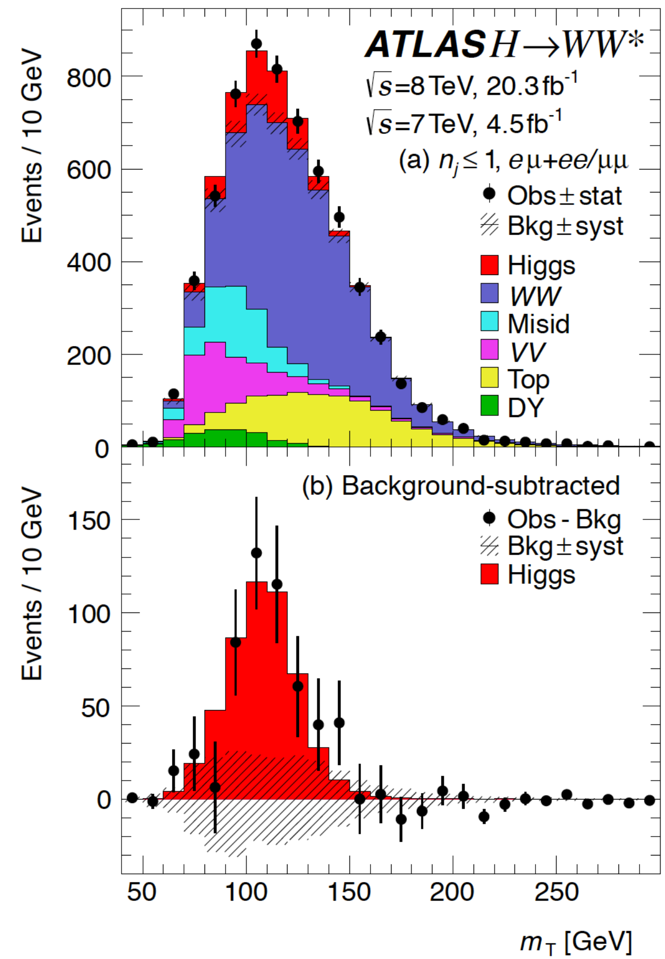
[Phys. Rev. D 92 (2015) 012006]

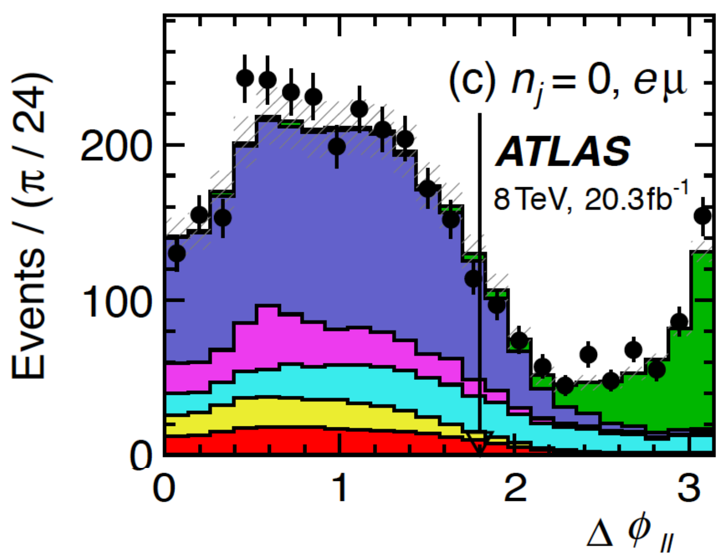


Divide into 0/1/2-jet regions (different background composition)

Has no mass sensitivity – fit to m_T (BDT) distribution for ggF (VBF) category, with one norm factor per control region







Due to spin correlation:

- Large pt(ll) – kill Z+jets
- Small mll
- Small ΔΦ(ll)

$$m_T = \sqrt{\left(E_T^{ll} + p_T^{\nu\nu}\right)^2 - \left|\mathbf{p}_T^{ll} + \mathbf{p}_T^{\nu\nu}\right|^2}$$

Signal strength:

$$\mu = 1.09^{+0.23}_{-0.21}$$

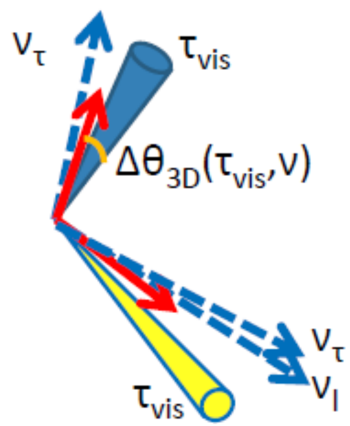
H→ττ

[JHEP 04 (2015) 117]

Leptonic and hadronic decays of taus

ee, eμ, μμ, eτ$_h$, μτ$_h$, τ$_h$τ$_h$

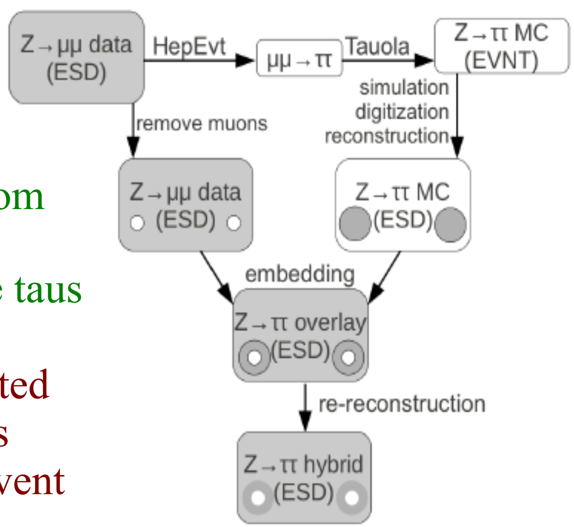
12% $\tau_{lep}\tau_{lep}$ 46% $\tau_{lep}\tau_{had}$ 42% $\tau_{had}\tau_{had}$



Use likelihood-based tautau mass reconstructions-MMC

Two signal regions: VBF and boosted (ggH)

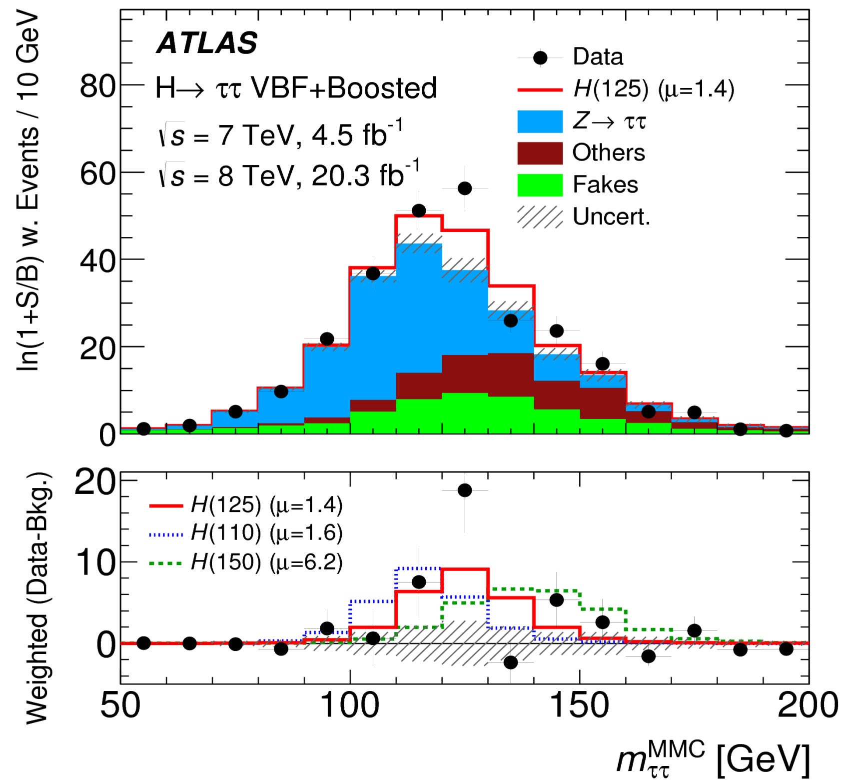
Use BDT for signal fit



Replace muons from Z→μμ data by taus and decay the taus

Embed the simulated tau decay products into the original event

MMC weighted by ln(1+S/B) in BDT bins:



Final fitted signal strength:

$$\mu = 1.43^{+0.27}_{-0.26}(\text{stat.})^{+0.32}_{-0.25}(\text{sys.}) \pm 0.09(\text{theo.})$$

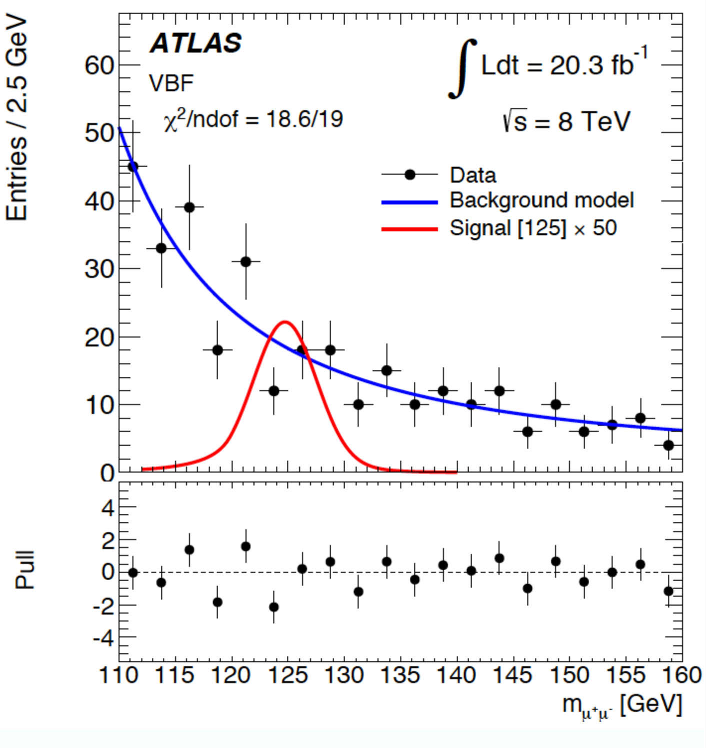
This corresponds to 4.5σ for 125 GeV (3.4σ expected)

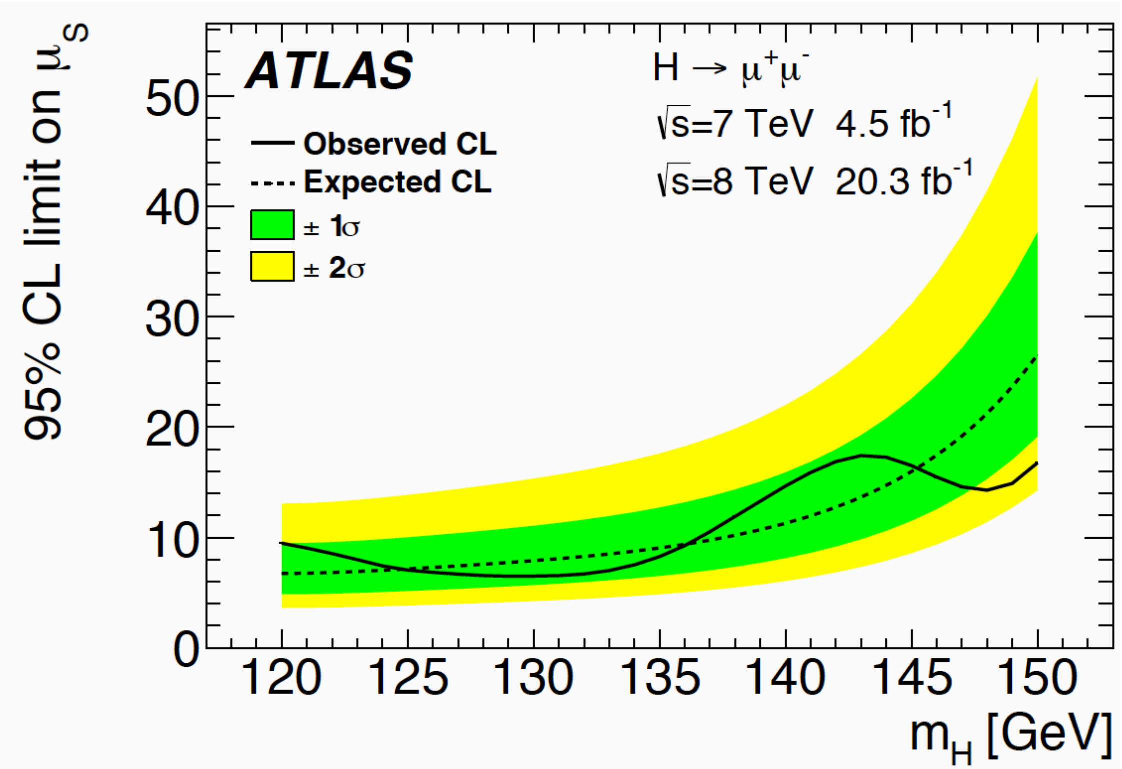
H→μμ

[Phys. Lett. B 738 (2014) 68]

➢ "Simple" analysis but made difficult by low branching fraction and overwhelming $Z/\gamma^* \rightarrow \mu^+\mu^-$ background

- Analysis categories: VBF / 3 separate $p_T(H)$ bins
- Result: observed μ < 7.0 (95% CL) (expected: μ < 7.2)

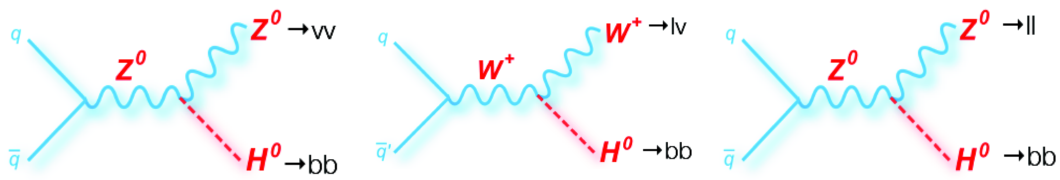




We'd better see this signal before building future $\mu^+\mu^-$ colliders

VH, H→$b\bar{b}$

[JHEP 01 (2015) 069]



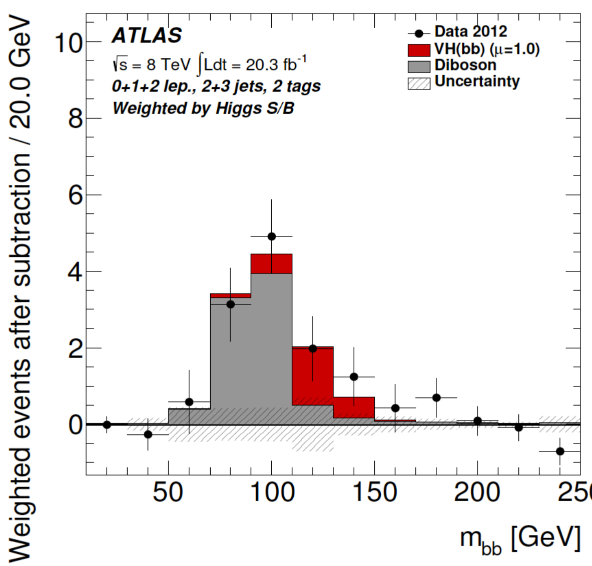
$ZH \rightarrow \nu\bar{\nu}b\bar{b}$ $WH \rightarrow \ell\nu b\bar{b}$ $ZH \rightarrow \ell^+\ell^- b\bar{b}$

Like H→ττ, important for Yukawa coupling measurment
Large BR, but large background

A SM Higgs in bbar decay is excluded for 1.2xSM rate.

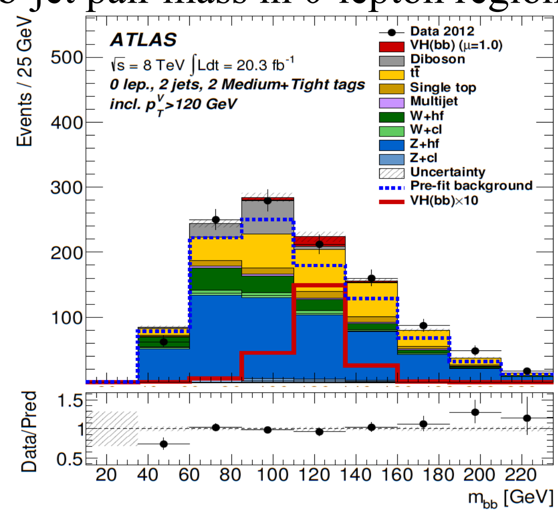
The fitted signal strength

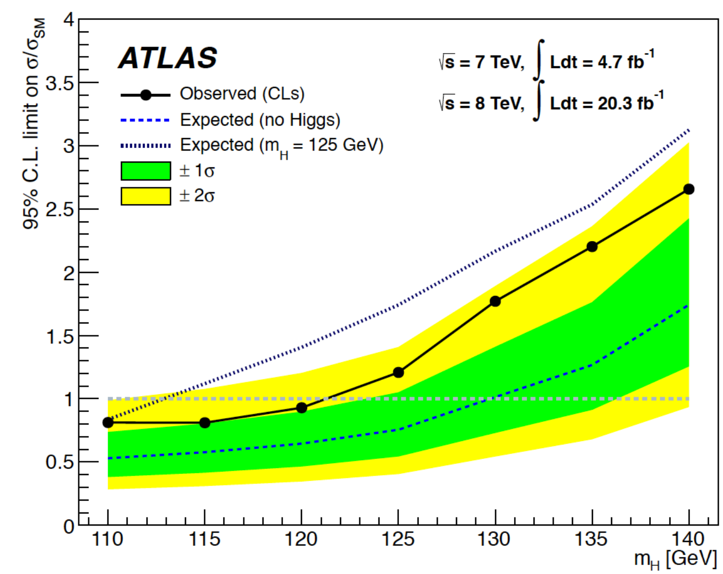
$$\mu = 0.51^{+0.31}_{-0.30}(\text{stat.})^{+0.25}_{-0.22}(\text{sys.})\quad \boxed{1.4\sigma}$$



Divide into 0/1/2-lepton regions (different background composition)
Two or 3 jets, 1-btag and 2-btag regions
Two $p_T(V)$ bins
Use BDT for signal fit
MET cut in 0/1-lepton
m_T cut in 1-lepton
m_{ll} cut in 2-lepton

b-jet pair mass in 0-lepton region





To validate the bbar analysis Method, the process decays of V+Z→bb is extracted to give

$$\mu = 0.74 \pm 0.09(\text{stat.}) \pm 0.14(\text{sys.})$$

– confidence in signal modeling

ttH, H→ $b\bar{b}$

[Eur. Phys. J. C (2015) 75:349]

Direct measurement of top Yukawa coupling y_t
Can be combined with indirect measurements

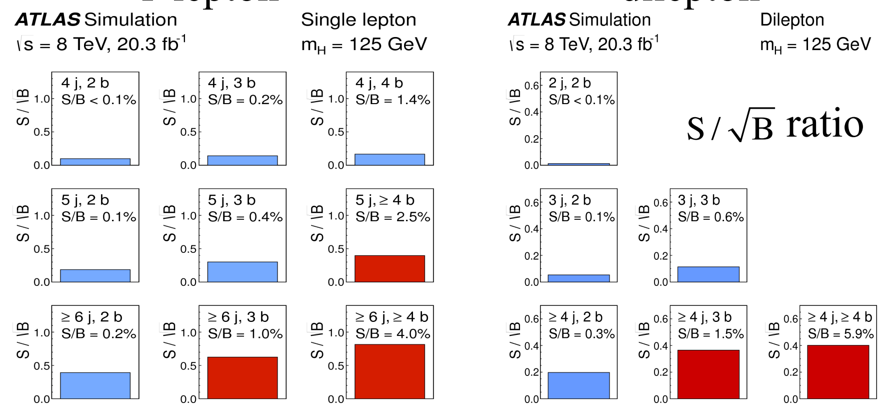
divide into 1- and 2-lepton regions, each is divided into different jet/b-jet multiplicity bins:

- low multiplicity bins used for background control
- high multiplicity bins used as signal regions

1-lepton	2 b-jets	3 b-jets	≥4 b-jets
4 jets	H_T	H_T	H_T
5 jets	H_T	NN	NN
≥6 jets	H_T	NN	NN

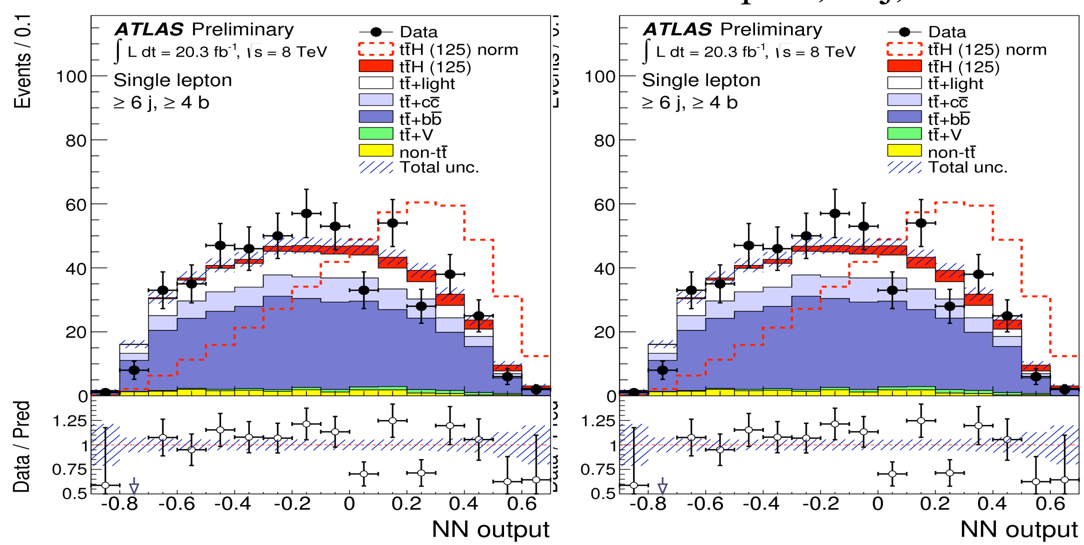
dilepton	2 b-jets	3 b-jets	≥4 b-jets
2 jets	H_T		
3 jets	H_T	NN	
≥4 jets	H_T	NN	NN

1-lepton dilepton



$S/\sqrt{B}$ ratio

NN in one most sensitive bin:1-lepton, ≥6j, ≥4b

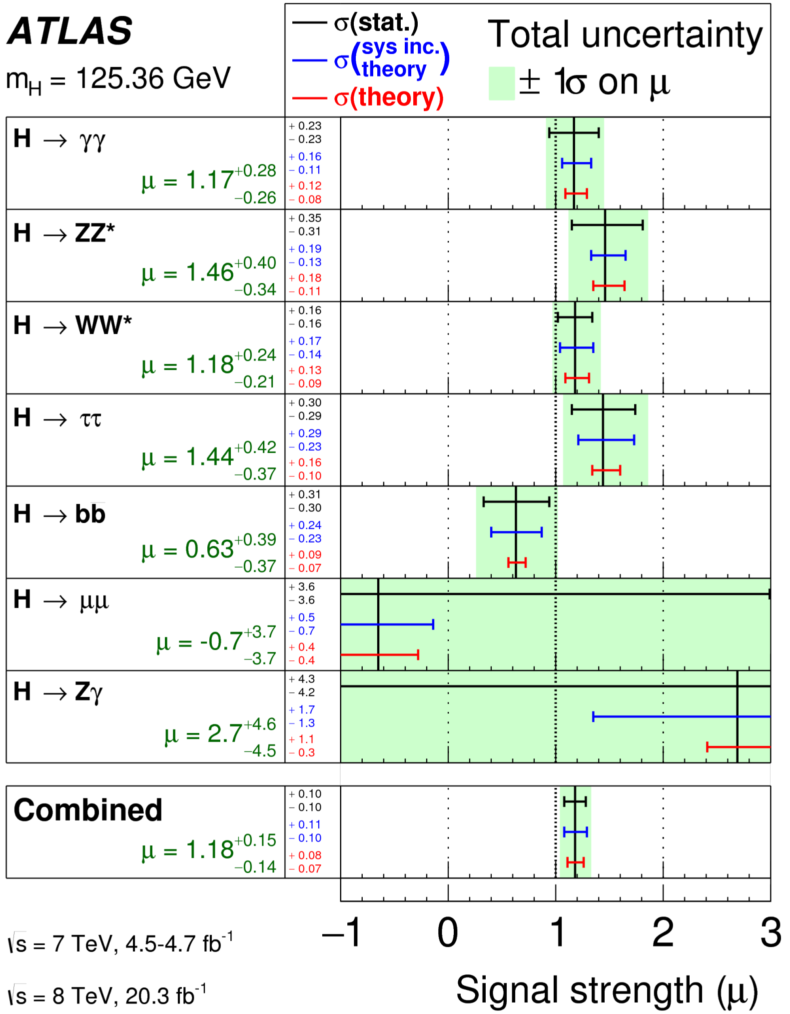


Use NN for signal extraction, H_T/NN to constrain systematics
Use Matrix Element for the 1-lepton channel (~16% improvement)

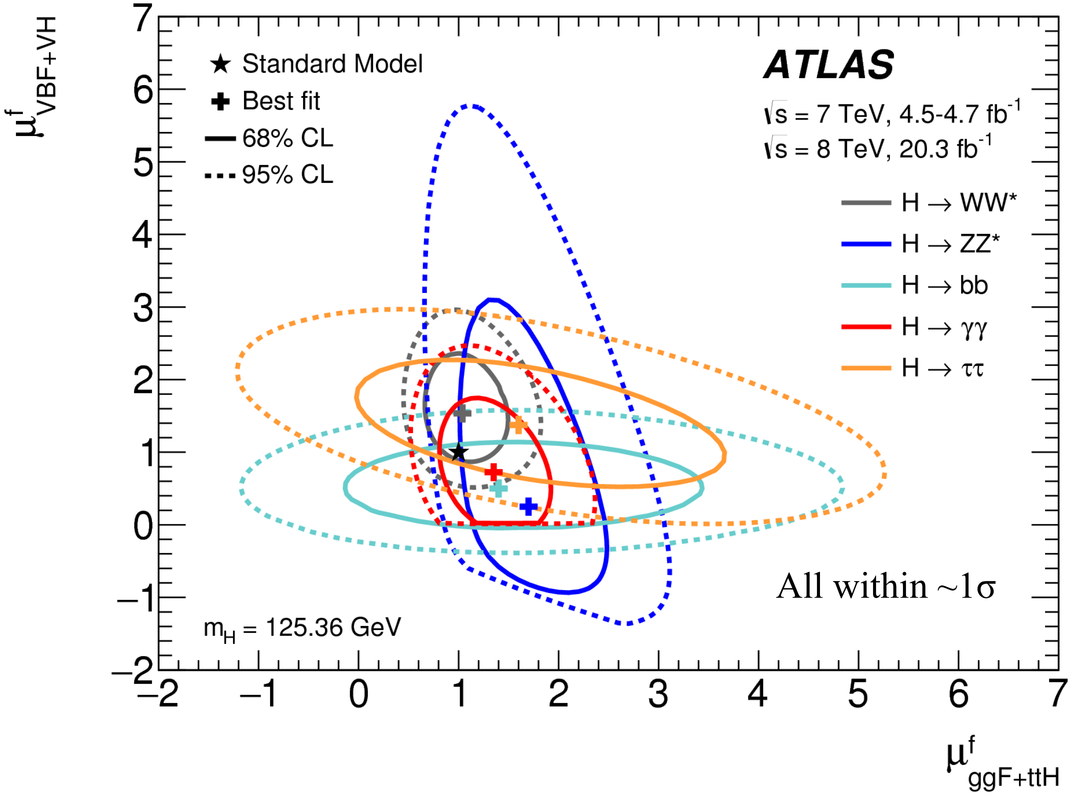
ttH(bb): 95% CL upper limit on μ:
3.4(2.2) for observed (expected)
Best-fit signal strength:
$\mu = 1.5 \pm 1.1$

[arXiv:1507.04548]

Higgs coupling combination



Signal strength: $\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{obs}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$



Combined μ: $1.18^{+0.15}_{-0.14}$

We assume:

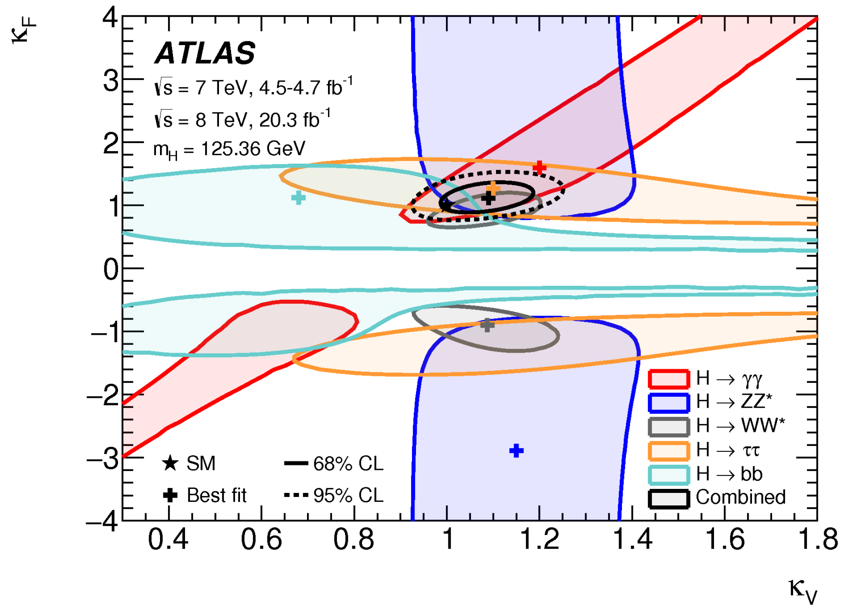
$$\mu_{\mathrm{ggH,ttH}} = \mu_{\mathrm{ggH}} = \mu_{\mathrm{ttH}}$$
$$\mu_{\mathrm{VBF,VH}} = \mu_{\mathrm{VBF}} = \mu_{\mathrm{VH}}$$

[arXiv:1507.04548]

Higgs coupling combination

Coupling strength:

$$\sigma \cdot \mathrm{BR}(i \to H \to f) = \frac{\sigma_i^{\mathrm{SM}} \cdot \Gamma_f^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}} \cdot \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}$$

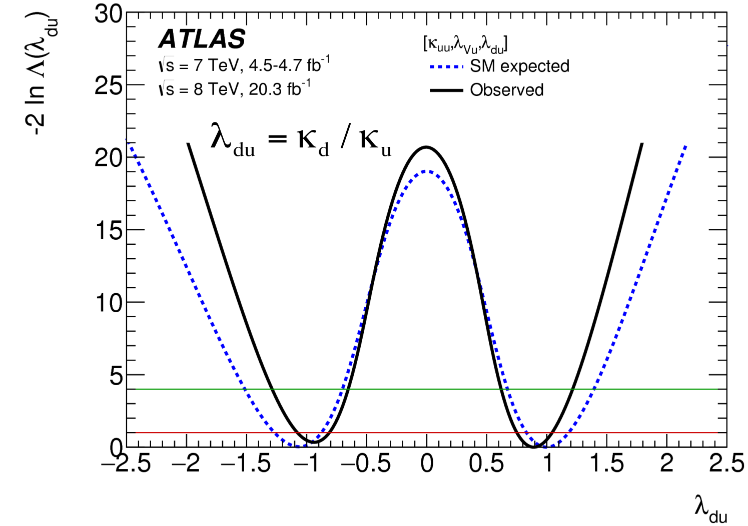


Double minima because of the H→γγ loop:

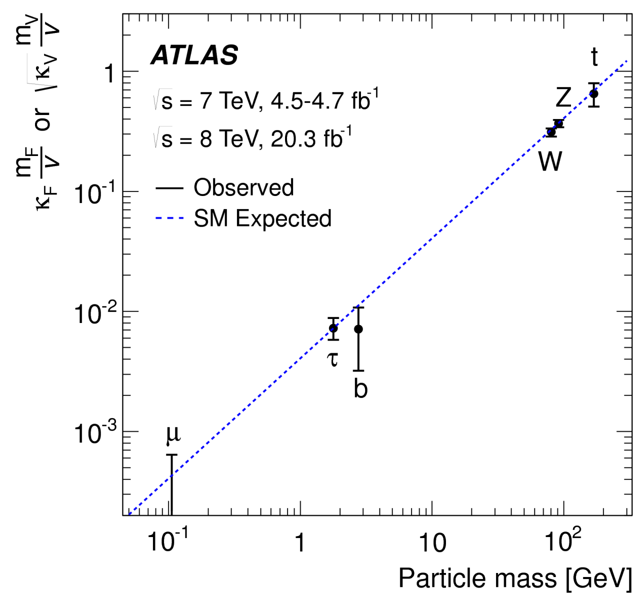
$$\sim \kappa_\gamma^2 = |1.28\ \kappa_W - 0.28\ \kappa_t|^2$$

- Probe coupling of Higgs boson to fermions and bosons
- $\kappa_F \bullet \kappa_V < 0$ is disfavored at the ~4σ level by profiling
- Assume only SM particles in the loop

Is the Yukawa coupling democratic in up- and down-type?



Is Higgs coupling proportional to mass?



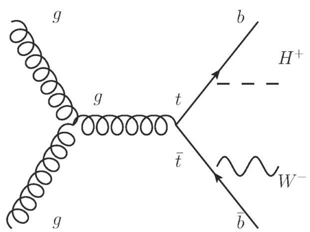
$$y_V \sim \sqrt{\kappa_V}\,\frac{m_V}{\upsilon}$$

$$y_f \sim \frac{\kappa_f m_f}{\upsilon}$$

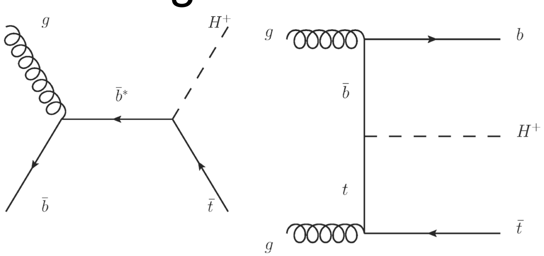
[JHEP03 (2015) 088]

Charged Higgs H→τν

Low mass:



High mass:



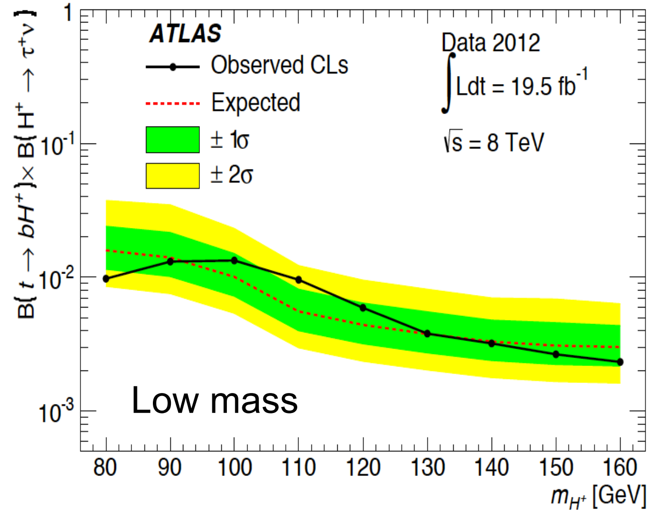
Search for all-hadronic mode (to construct m_T), and require tau+MET trigger

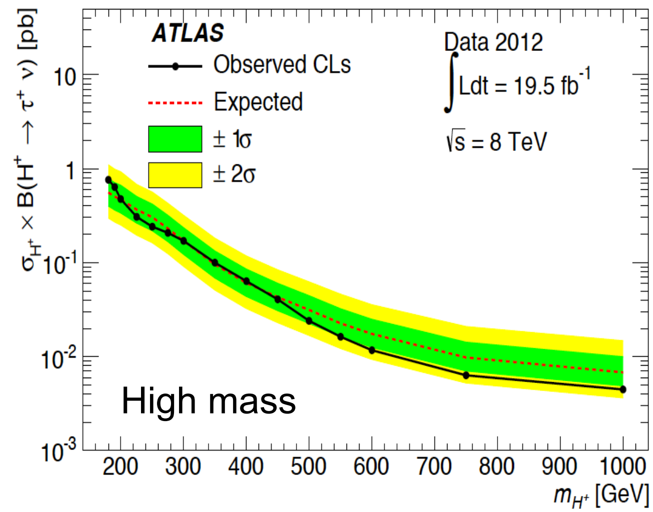
3/4 jets, ≥1 b-jet

Large MET

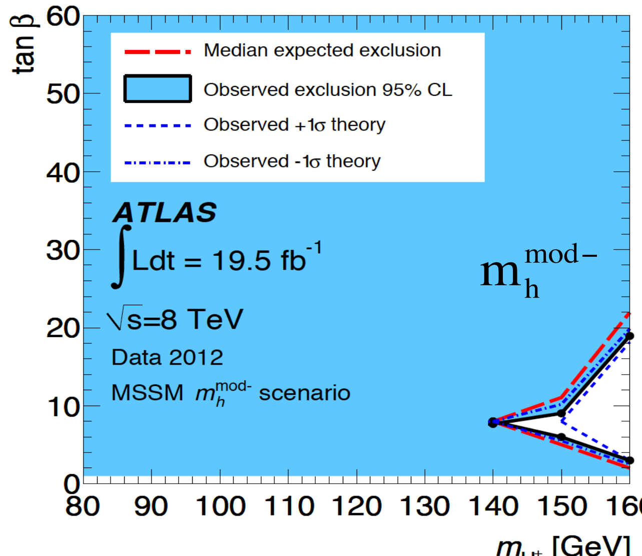
Bench mark models $m_h^{mod\pm}$ has parameter tuning such that the light Higgs mass is consistent with 125 GeV

- Model independent search limits:

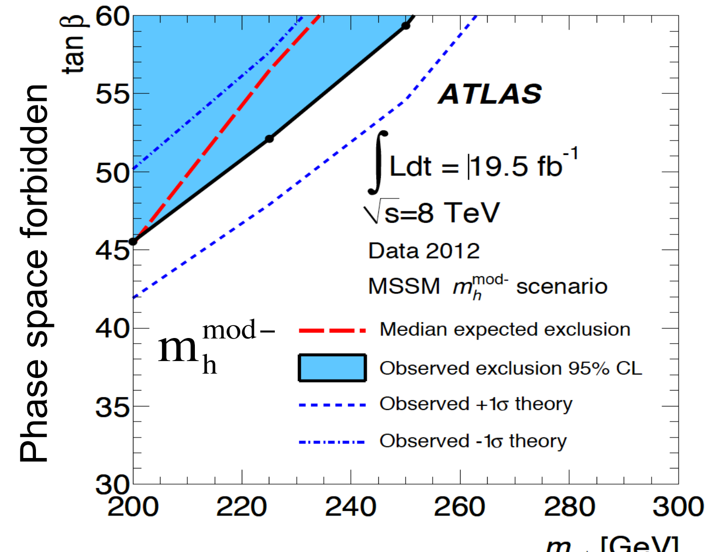




- MSSM interpretation:



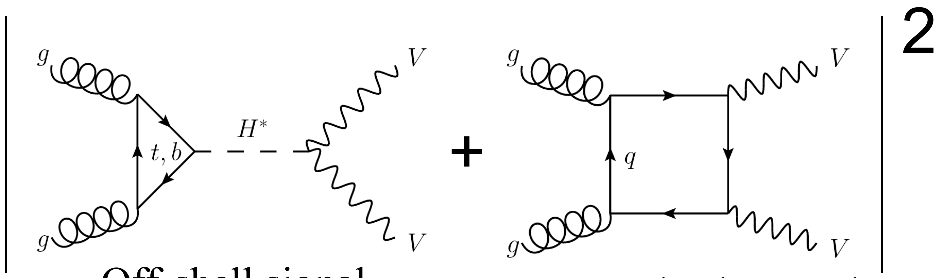
Low mass



High mass

Probing the off-shell Higgs

Combined 3 channels: ZZ→4l, ZZ→2l2ν, WW→eνμν



Off-shell signal
gg→H*→VV

ggVV background
(interfere with signal)

Measure VV differencial process to probe off-shell Higgs:

$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

Denote $R^B_{H^*}$ for the ratio of gg→H*→VV and ggVV (σ for the latter process not well known)

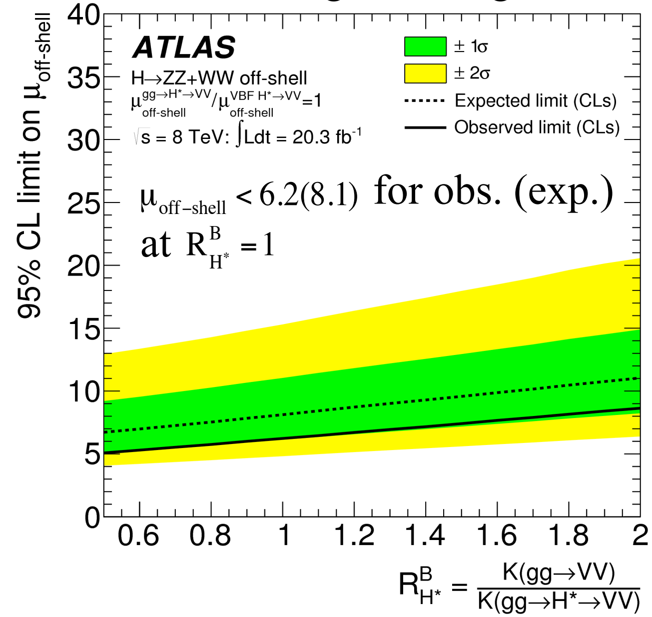
For ZZ→4l final state, calculate the Matrix Element for each event using MCFM (can fully construct the initial and final state particles' 4-momenta)

For ZZ→2l2ν and WW→eνμν, m_T is used to construct the discriminant

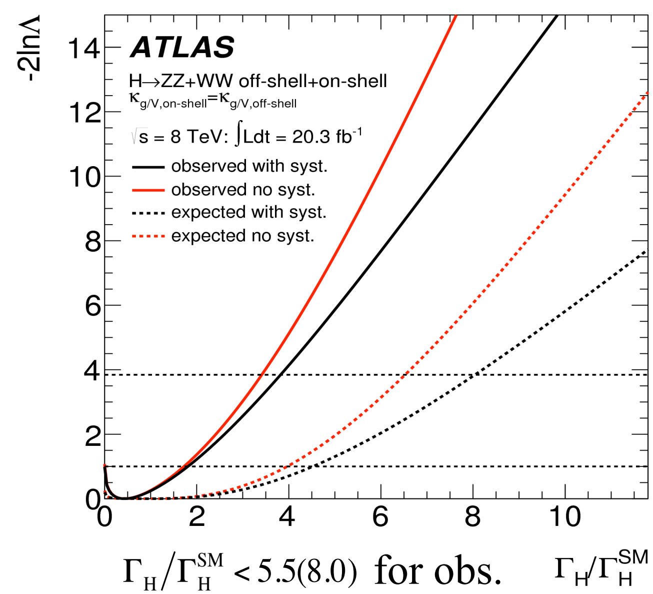
When combined with the on-shell measurements to estimate Higgs width (caveat: many assumptions made):

$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

The off-shell signal strength limit:



$\mu_{\text{off-shell}} < 6.2(8.1)$ for obs. (exp.) at $R^B_{H^*} = 1$



$\Gamma_H/\Gamma_H^{SM} < 5.5(8.0)$ for obs. (exp.) at $R^B_{H^*} = 1$

Higgs → invisible

[ATLAS-CONF-2015-004]

VBF Higgs→ invisible:

- Require MET trigger
- Basically rate counting
- Have dedicated Zll and Wlν control regions

Process	Yield ±	Stat ±	Syst
ggH Signal	20 ±	6 ±	10
VBF Signal	286 ±	5 ±	49
$Z \to \nu\nu$+jets	339 ±	22 ±	13
$W \to \ell\nu$+jets	237 ±	17 ±	18
Multijet	2 ±	2	
Other Backgrounds	0.7 ±	0.2 ±	0.3
Total Background	578 ±	38 ±	30
Data	539		

95% CL Upper limit result:

$\mathrm{BR}(H \to \mathrm{invisible}) < 0.29$

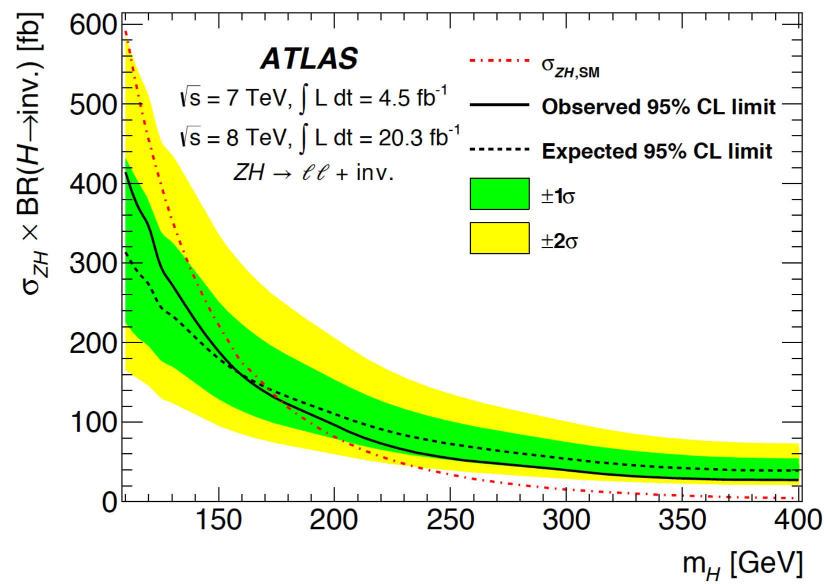
(<0.35 is expected)

[Phys. Rev. Lett. 112 (2014) 201802]

VH with H→ invisible:

- ZH→ll+invisible

$\mathrm{BR}(H \to \mathrm{invisible}) < 0.75$ (0.62 exp.)



[Eur. Phys. J. C (2015) 75:337]

- VH→jj+invisible

$\mathrm{BR}(H \to \mathrm{invisible}) < 0.78$ (0.86 exp.)

[ATLAS-HIGG-2015-03-002]

Combining 3 direct searches: $\mathrm{BR}(H \to \mathrm{invisible}) < 0.25$ (0.27 exp.)

Higgs tensor coupling

[ATLAS-CONF-2015-008]

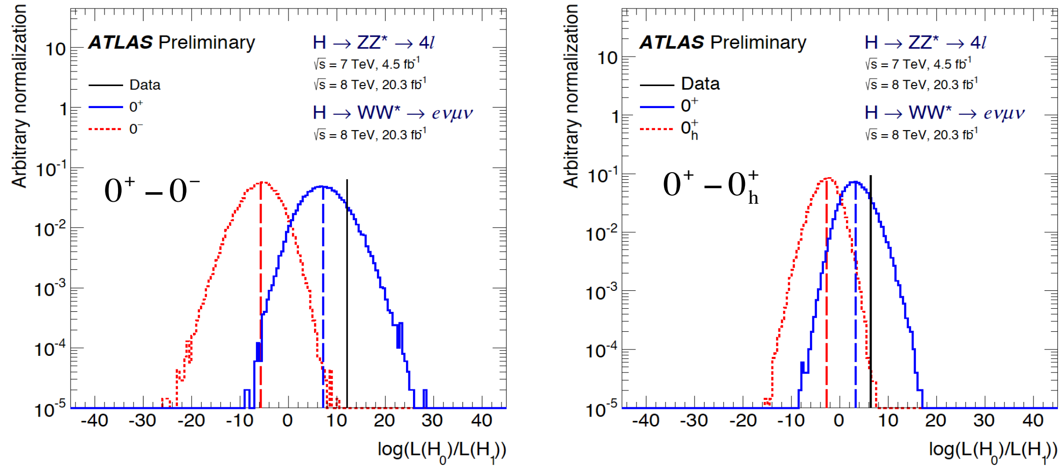
Use Effective Field Theory to probe Higgs HVV tensor structure (for spin-0):

$$\begin{aligned}\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM}\left[\boxed{\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu}}\right] \\ & -\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\boxed{c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu}} + \boxed{s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}}\right] \\ & -\tfrac{1}{2}\tfrac{1}{\Lambda}\left[\boxed{c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu}} + \boxed{s_\alpha \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu}}\right]\Big\} X_0\end{aligned}$$

$$c_\alpha = \cos\alpha, \quad s_\alpha = \sin\alpha$$

SM 0^+ BSM CP-even 0^+_h BSM CP-odd 0^-

Fixed CP Higgs tests:



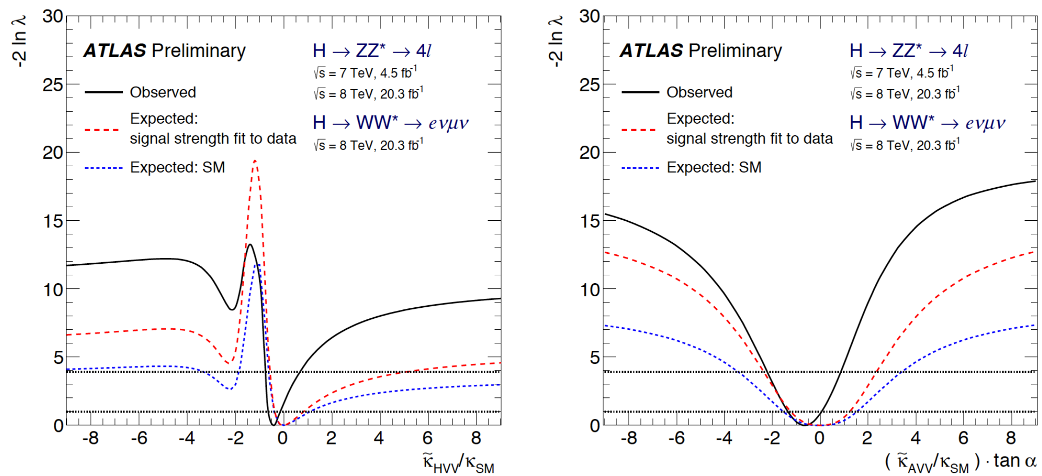
Combined 3 channels: WW→eνμν, γγ, ZZ→4l

WW→eνμν 0-jet: $m_{ll}, \Delta\phi_{ll}, p_T^{ll}, E_{ll\nu\nu}, \Delta p_T$

γγ: Collins-Soper frame angle and diphoton p_T

ZZ→4l: angles $\theta^*, \Phi_1, \Phi, \theta_1, \theta_2$ and BDT_{ZZ} (to reject ZZ background)

Mixed CP Higgs tests:



We can also consider the mixture of SM and BSM CP even/odd

Limits on the BSM and SM coupling ratio can be set:

$$\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{AVV}$$

$$\tilde{\kappa}_{HVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{HVV}$$

Coupling ratio	Best fit value		95% CL Exclusion Regions	
Combined	Expected	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{SM}$	0.0	−0.48	$(-\infty, -0.55] \bigcup [4.80, \infty)$	$(-\infty, -0.73] \bigcup [0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$	0.0	−0.68	$(-\infty, -2.33] \bigcup [2.30, \infty)$	$(-\infty, -2.18] \bigcup [0.83, \infty)$

LFV H→μτ

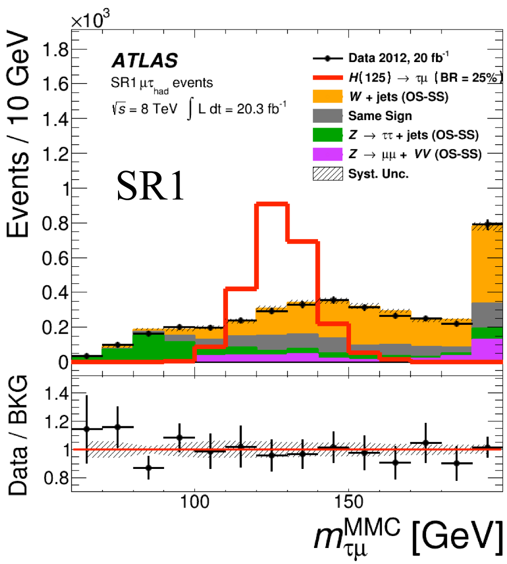
[arXiv:1508.03372]

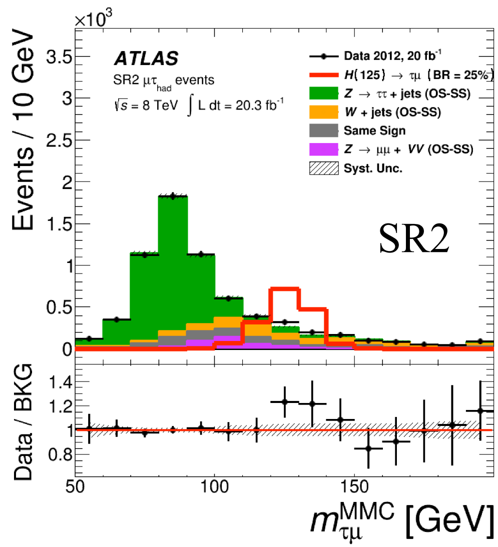
BR(H→eμ)<O(10^{-8}) due to μ→eγ constraint, but the constraint is less for other Lepton-Flavor-Violating (LFV) decays:
BR(H→eτ,μτ)<O(10%)

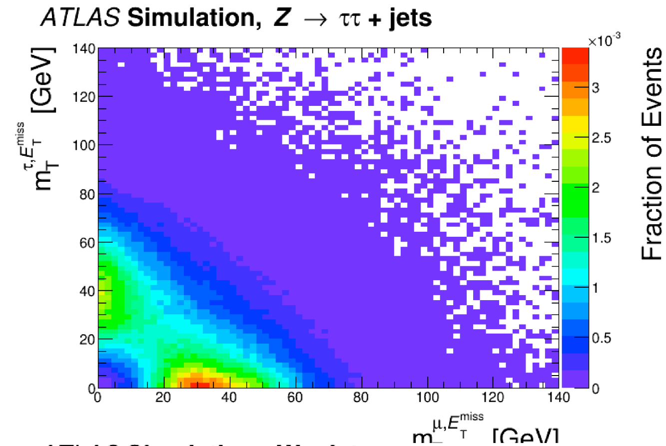
Use transverse mass to separate signal and background, and define 2 signal regions:

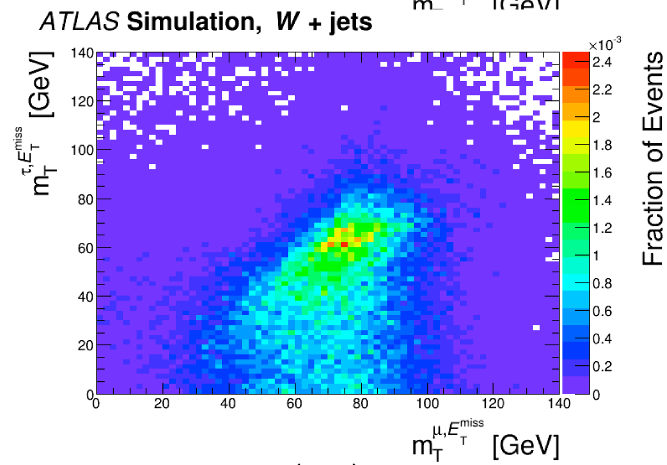
$$\text{SR1:}\quad m_T(\mu,E_T^{miss}) > 40\text{GeV}, m_T(\tau,E_T^{miss}) < 30\text{GeV}$$

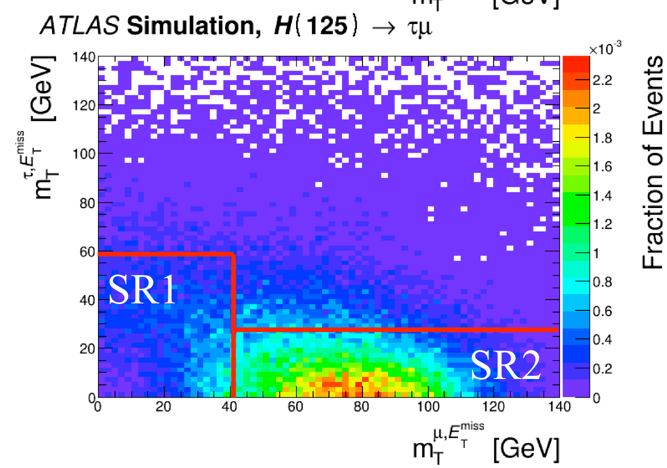
$$\text{SR2:}\quad m_T(\mu,E_T^{miss}) < 40\text{GeV}, m_T(\tau,E_T^{miss}) < 60\text{GeV}$$









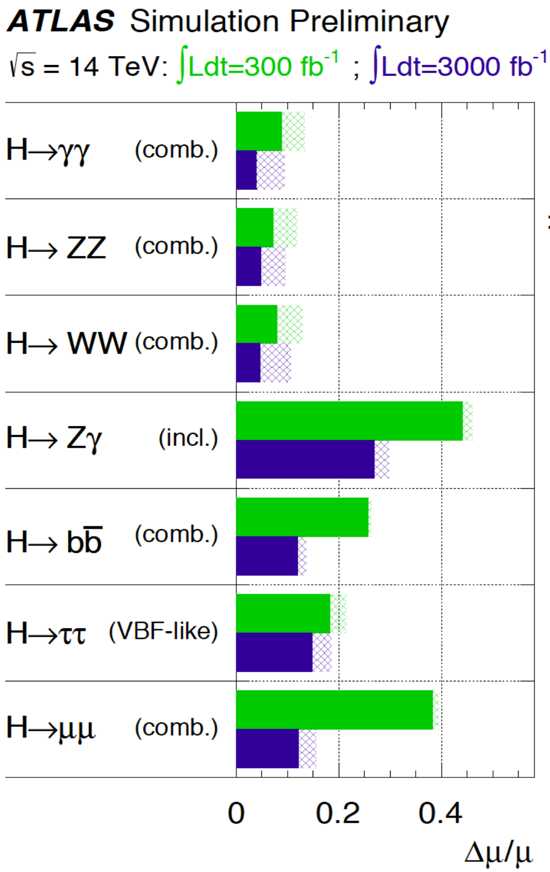


Fit to the MMC spectrum to extract signal:

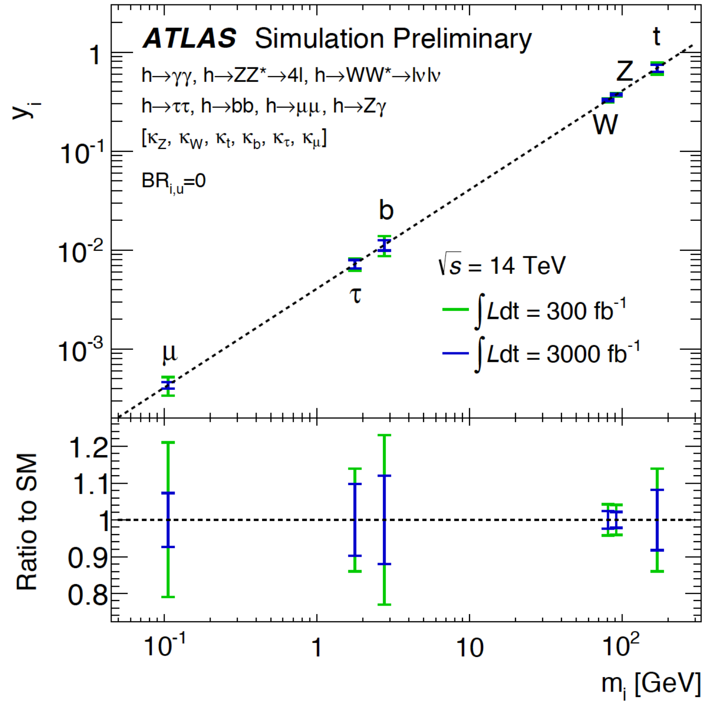
$$\boxed{\text{BR}(H \to \mu\tau) = (0.77 \pm 0.62)\%}$$

[ATL-PHYS-PUB-2014-016/017]

Higgs prospects for Run2/3



Coupling versus mass:

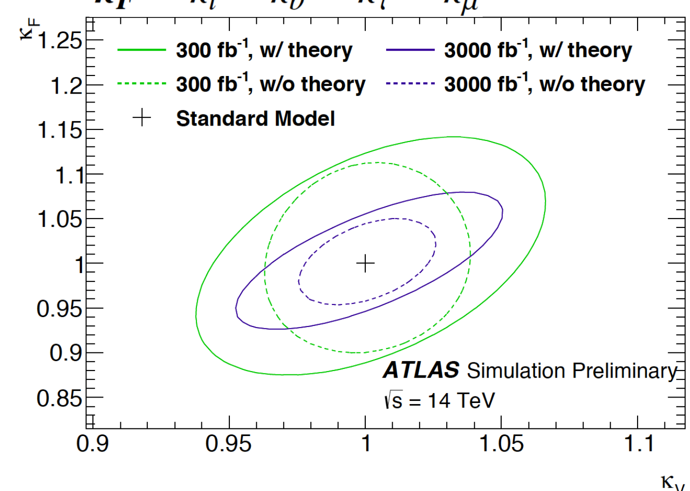


Errors on individual factors:

Nr.	Coupling	300 fb^{-1} Theory unc.: All	Half	None
8	κ_Z	8.1%	7.9%	7.9%
	κ_W	9.0%	8.7%	8.6%
	κ_t	22%	21%	20%
	κ_b	23%	22%	22%
	κ_τ	14%	14%	13%
	κ_μ	21%	21%	21%
	κ_g	14%	12%	11%
	κ_γ	9.3%	9.0%	8.9%
	$\kappa_{Z\gamma}$	24%	24%	24%

$$\kappa_V = \kappa_Z = \kappa_W$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$$



More precise measurements of Higgs production and decay rates: ~10% (~20%) for the boson (fermion) decay

More precise determination of the Higgs mass and width

Test of the SM in the Higgs sector and probe for new physics such as MSSM, rare/new/invisible Higgs decay

Use EFT and differential variables for advanced Higgs property tests

Summary

After Higgs boson discovery, main focus has shifted to its property measurements:

Its precise mass determination ($\gamma\gamma$ and ZZ$\rightarrow$4l)

Its couplings to different SM particles (bosons and fermions)

Its spin/CP, and its tensor couplings

Its total width, other BSM decays (such as invisible)

Most Run 1 Higgs results are finalized with improved methods, sensitivity and errors. Our understanding of the new particle has been pushed to an unprecedented level

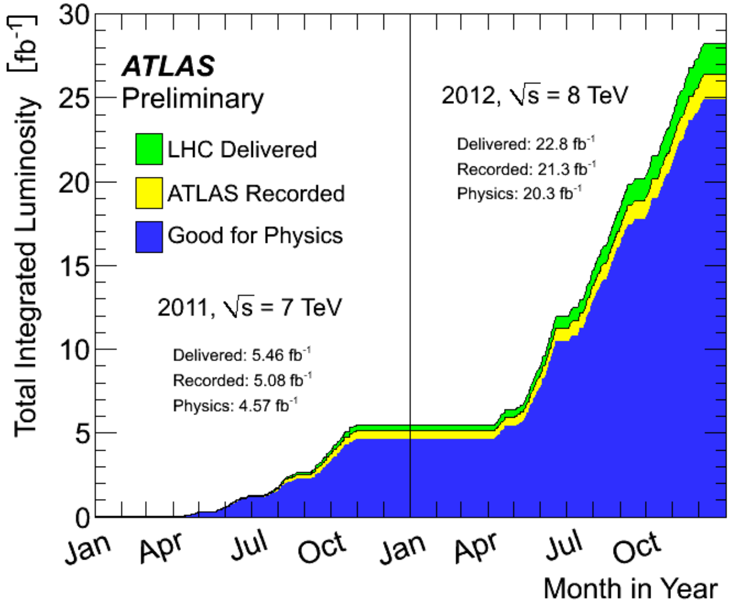
Combination of coupling measurements are always made to test any deviations from SM predictions. So far, no significant deviations are observed

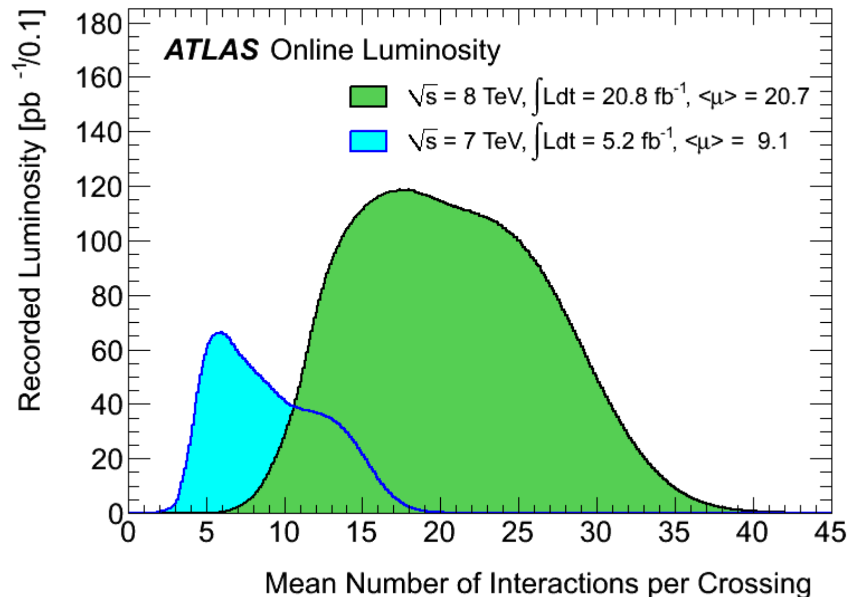
Not all analyses are covered in this talk (some measurements with Run 1 are still on-going. Most analyses are geared toward precision measurements with Run 2 – please keep tuned!

Extra Slides

ATLAS Luminosity in Run 1 & 2

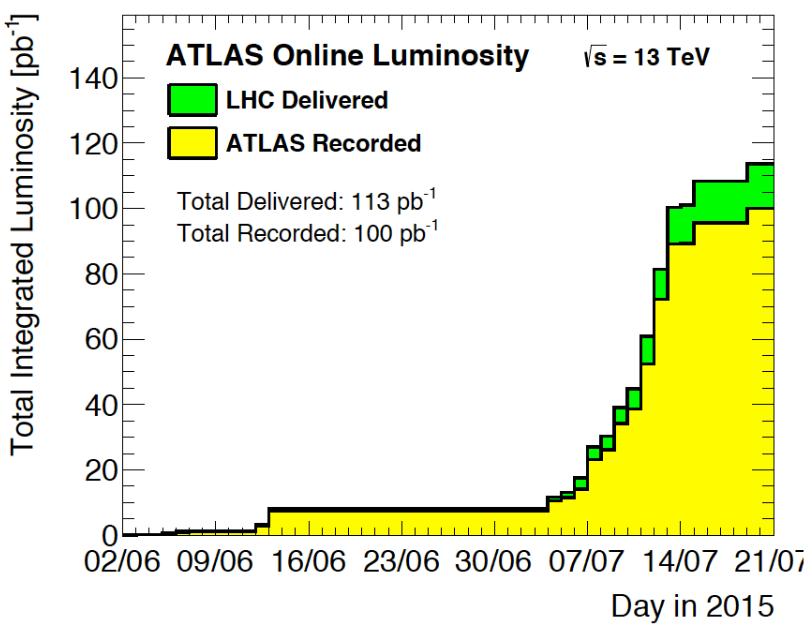
Run 1

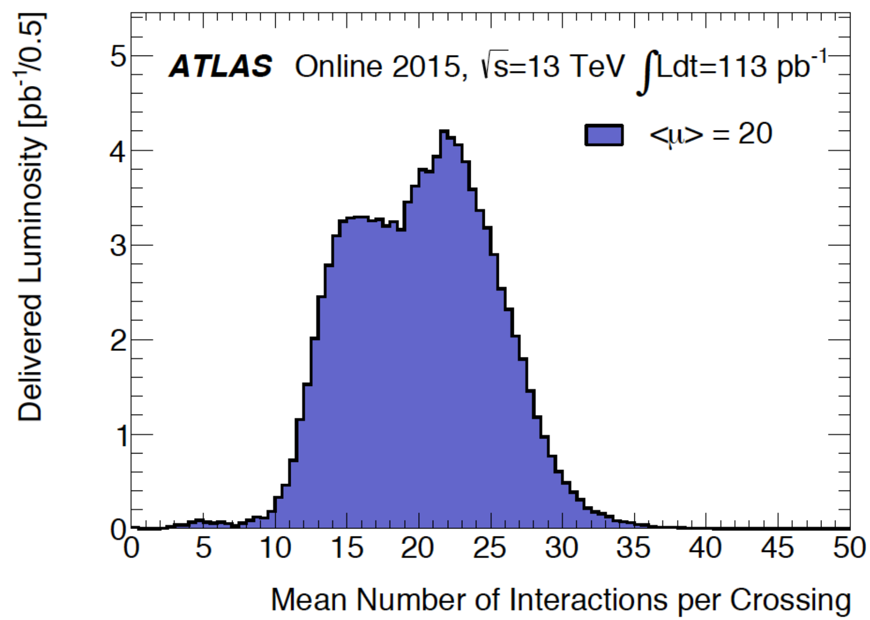




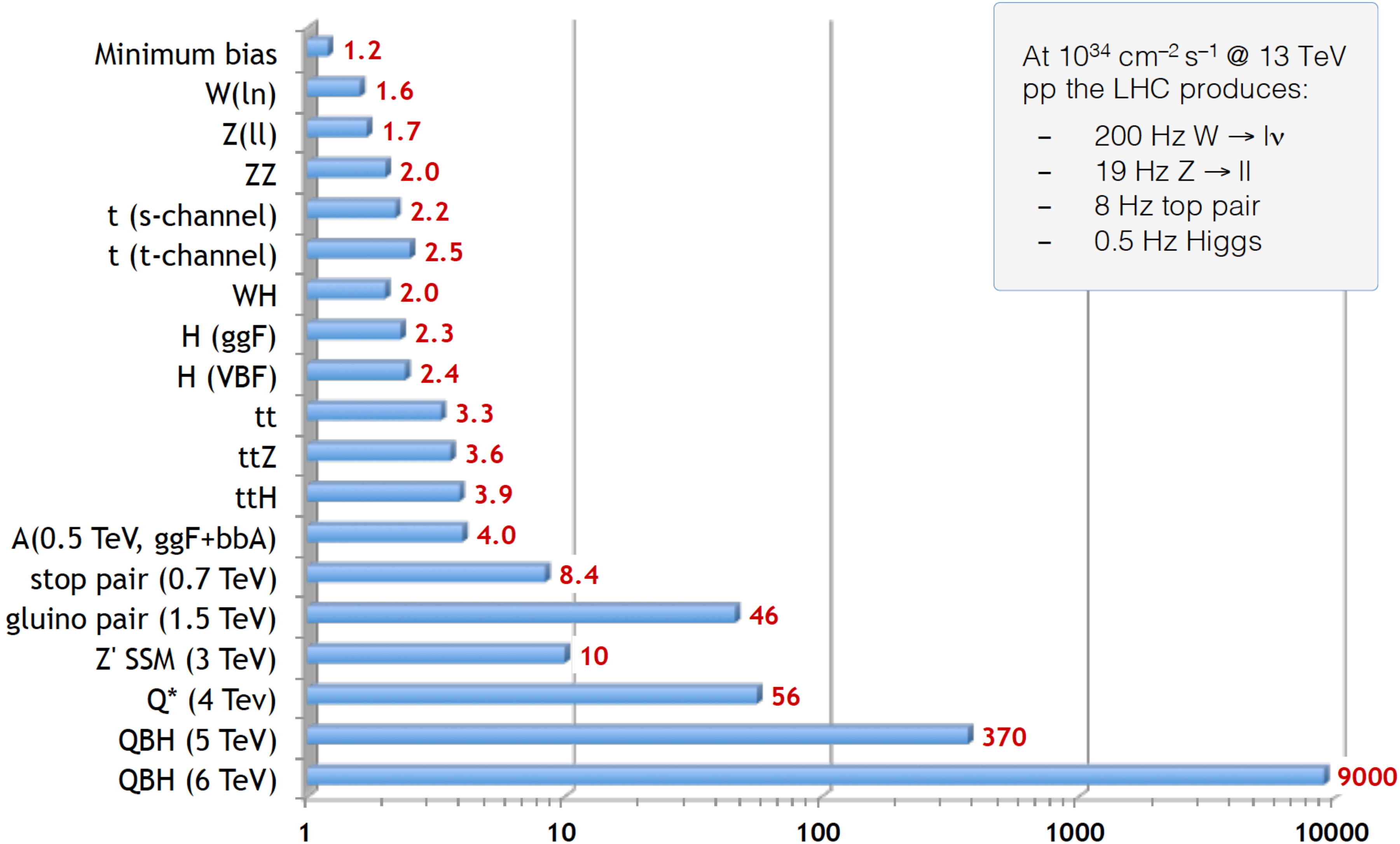
Pileup interactions profile

Run 2





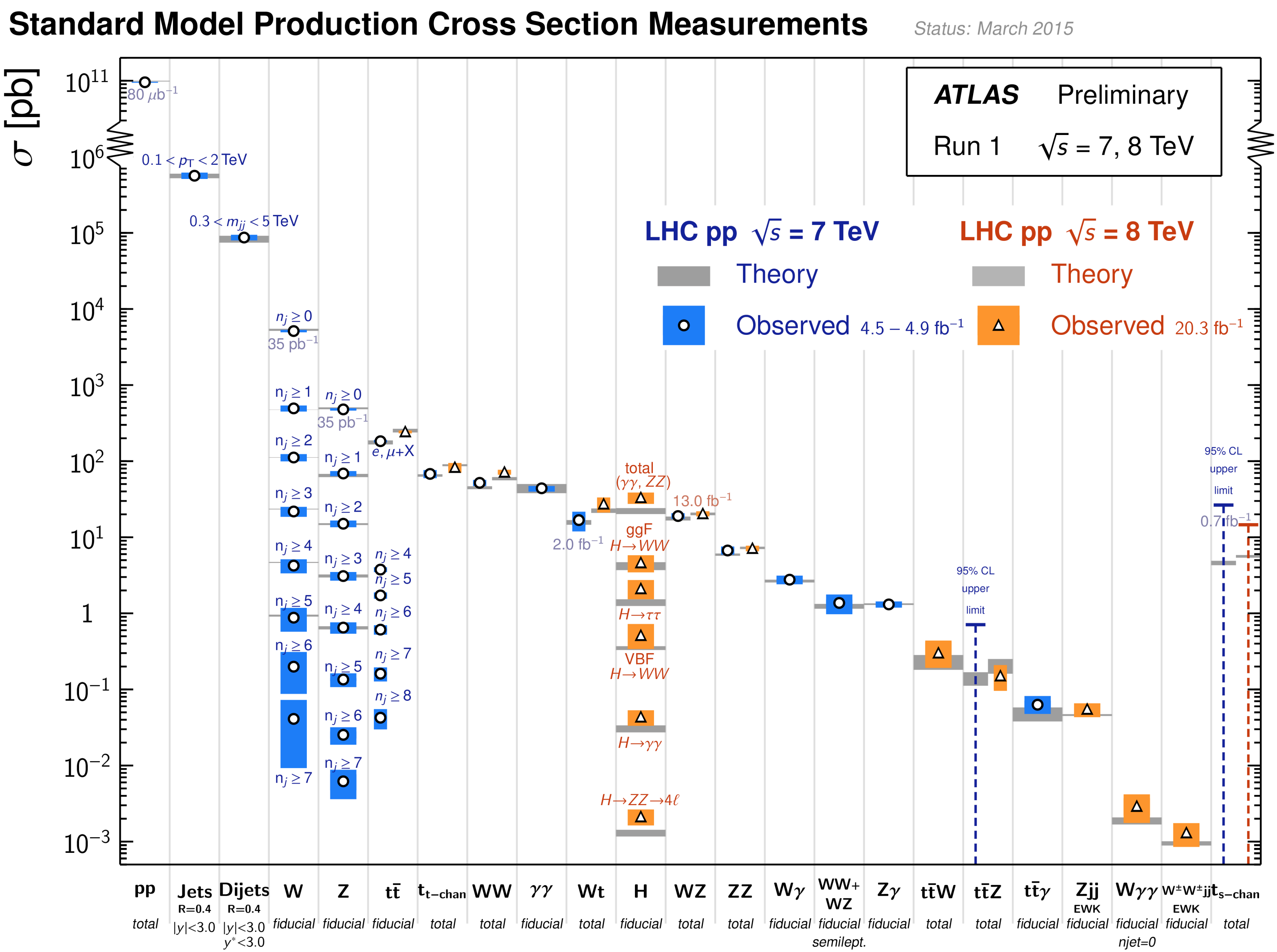
Scaling factors from 8 to 13 TeV



At 10^{34} cm^{-2} s^{-1} @ 13 TeV pp the LHC produces:

- 200 Hz W → lν
- 19 Hz Z → ll
- 8 Hz top pair
- 0.5 Hz Higgs

Confirming SM prediction with Run 1



LHC Schedule